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THE RESISTIVITY OF HARDENED CAST IRON AS A MEASURE OF ITS TEMPER AND OF ITS FITNESS FOR USE IN PERMANENT MAGNETS.

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With a Plate.

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It has long been known that the specific electrical resistance of a piece of soft tool steel is materially less than that of the same piece after it has been hardened, and that the relaxing of the temper of any piece of steel or iron makes the specific resistance less; but the first systematic study of this phenomenon was made by Messrs. Barus and Strouhal whose work is summarized in Bulletin 14 of the U. S. Geological Survey.[1]

In one experiment which these gentlemen made upon rods of "English Silver" steel, 0.15 cm. in diameter and all originally glass-hard, different pieces were tempered by heating them to different fairly high temperatures, as indicated by the oxide tints on their surfaces, and were then cooled. When the specimens thus treated were tested it appeared that the harder the temper, the higher was the specific resistance (s) referred to the centimeter cube, and the lower the temperature coefficient (a) of the specific resistance. In the case of a certain glass-hard rod, s, in microhms, was 45 and a was 0.0016; while in a thoroughly annealed rod of the same lot, s was 16 and a about 0.0040. From these

[1] Wiedemann, Lehre von der Elektricität, Vol. I, p. 502; Benoit, Comptes Rendus. **76**, 342 (1873); Matthiessen and Vogt, Pogg. Ann., **122**, 10 (1864); Auerbach, Wied. Ann., **5** (1878); Wied. Ann., **8**, 479 (1879); Callendar, Phil. Trans. 1887; Strouhal and Barus, Wied. Ann., **11**, 976 (1880); Barus, Phil. Mag., **8**, 341 (1879); Chernoff, Vortrag gehalten in der Russischen Technischen Gesellschaft, 1868; Jarolimek, Dingler's Journal, **221**, 436 (1876); Jarolimek and Ackermann, Zeitschrift für das Chemische Grossgewerbe, 1880; Percy-Wedding, Eisenhüttenkunde, II, p. 130, 1864; Karsten, Karsten und von Dechen's Archiv, **25**, 223 (1853); Barus and Strouhal, Bulletin of the United States Geological Survey, No. 14; Caron, Comptes Rendus, **56**, 43 (1863); Barus, Physical Review, **30**, 348 (1910).

TABLE I.

s.	a.	s.	a.
10	0.0050	30	0.0024
12	46	32	22
14	42	34	21
16	39	36	20
18	36	38	19
20	34	40	18
22	32	42	17
24	29	46	16
26	27	50	15
28	26	60	14

and similar experiments, Barus and Strouhal made out a table connecting s and a which they subsequently found to fit other kinds of steel pretty well. Some of their results are given in Table I.

If corresponding values of s and a be used as coördinates, a fairly smooth curve results, and the mean values of 79 for s and 0.0013 for a which Barus and Strouhal got for three pieces of cast iron which they tested, yield a point which seems to lie closely enough upon the prolongation of this curve. It appears also that the values of s and a which Matthiessen, Vogt, and Benoit obtained for different kinds of wrought iron agree numerically with the values for steel; and some persons have thought that it is possible to determine the position of any piece of iron or steel in the scale of mechanical hardness, without any knowledge of the percentage of combined carbon, by finding s alone.

For bar magnets or for simple bent magnets, fine tool steel, or better, some of the kinds of special magnet steel, serve very well, but if a permanent magnet is required of such a shape that the steel has to be heated red hot a number of times during the process of forging and before it is made glass-hard, irregular temper thus introduced into the material often shows itself in the presence of irregular magnetization when the magnet is finally charged, and this sometimes makes the magnet worthless. For this and other reasons, some makers of electrical instruments are now using chilled cast iron for such magnets, and these have usually proved to be satisfactory. They are cheap, they can be made quite as strong as tool steel magnets of the same dimensions, they are very permanent after they have once been aged,

and the temperature coefficients of their magnetism are almost always much smaller than those of forged steel magnets. Cast iron for permanent magnets must, however, be really hard, and, unfortunately, mechanical tests of the hardness of this metal are often deceptive; it seems desirable, therefore, to inquire whether the electric resistivity of a piece of chilled cast iron is a criterion of its temper.

This paper gives briefly a few of the results of a large number of observations made originally with the object of testing the relative efficiencies of different methods of hardening cast iron for magnets, in use in the Jefferson Laboratory. The details of this work have mainly a local interest and are not enumerated here, but some general facts may be useful to persons who have to make such magnets for themselves.

Each of the test pieces was a rod about 30 cms. long and a little less than 0.6 cm. in diameter. These were all milled down from stouter pieces about 1.5 cms. in diameter which were usually cast in sets of a dozen from a grid pattern to insure that they should be of the same kind of iron. Different specimens from the same grid, however, often showed different resistivities before they were annealed and occasionally one or two pieces from a grid would differ sensibly from the other pieces after all had been softened with great care. These differences are to be expected, as Karsten showed long ago, for the outer layers of a mass of chilled cast iron sometimes contain a greater proportion of combined carbon than the inner layers in which most of the carbon may be free, and an unequal chilling of a grid in the mould would naturally make the material slightly different in different parts. It is easy in practice to avoid abnormal specimens. All the test pieces were prepared, annealed, and hardened by Mr. George W. Thompson, the mechanician of the Jefferson Laboratory, whose experience in treating cast iron extends over many years.

The measurements of the specific resistances of the rods (usually three for each specimen) were mostly made with the help of a standard Kelvin Double Bridge, but in a few cases the test piece was connected in series with a standard manganin resistance bar and a constant storage battery, and the small potential drop across a measured length of the rod was compared with the corresponding drop across the standard. Three commutators were used with this apparatus so that the effects of disturbing electromotive forces at the contacts might be avoided. The ultimate standard was Wolff No. 2718 furnished with the certificate of the Reichsanstalt.

In the determinations of the temperature coefficients of resistivity two large tanks of water were used. One of these was approximately at room temperature. The water in the other, which was kept in

constant motion by a set of four propellers run by a small motor, was heated to a constant definitely determined temperature by means of a Simplex Electric Heater attached to a 110 volt circuit and dominated through a relay by a delicate thermostat. The annealing effects of very hot water upon hard cast iron had to be avoided, but the water in the second tank was usually made uncomfortably warm for the hand.

In making cast iron magnets, it is very necessary that the iron just before it is chilled shall be much hotter than it is safe to heat ordinary tool steel in making it hard. Dr. Campbell, of the National Physical Laboratory, Teddington, Middlesex, England, finds that a temperature of 1000° C. has been sufficient for the iron he has used, but some specimens of American iron seem to work best at a slightly higher temperature, just below the melting point. If a massive piece of cast iron weighing, say, fifty pounds be heated thus hot and then chilled in a proper bath, the material, as magnetic tests can be made to show, becomes hard throughout, whereas it is practically impossible to make a similar piece of tool steel glass-hard inside. The experiments of Chernoff upon a certain kind of steel, made more than forty years ago, showed that if the temperature from which the steel was chilled was made higher and higher, from, say, 400° C., the hardening effect was almost inappreciable until a cherry red was reached, when suddenly the chilled specimen was found to be glass-hard. It is not very surprising, therefore, that cast iron shows very little temper when chilled from a temperature of 800° C. or 900° C., but may easily be made glass-hard if its temperature just before the chilling is high enough, say 1050° C. for some kinds.

The rods were heated for the hardening, under a compressor blast, in a special gas furnace made for the purpose by Messrs. J. Connors and J. Coulson, and most of them were placed inside an iron tube to protect them from direct exposure to the flames. In annealing the rods they were packed in iron filings inside an iron tube closed at the ends by screw caps and heated thoroughly to a white heat for possibly 30 minutes before the tube was packed in ashes for many hours. Although the work was done with the greatest care, it soon appeared that it is usually impossible, at least by this particular annealing process, to bring a piece of cast iron once made glass-hard back to as low a resistivity as it originally had, and if the piece be repeatedly hardened and annealed, its resistivity in the relaxed state increases every time the cycle is passed through. The diameter of the piece also increases perceptibly much as the cast iron bars of a fire box grate grow longer with hard use. Two or three examples will show the complicated nature of the phenomena involved.

Two test pieces from the Broadway Iron Works, Cambridgeport, were annealed as they came from the foundry and then had resistivities 102.5 and 102.7 and a diameter of 0.574 cm. After both had been hardened, the resistivities at about 20° C. were 122.5 and 122.0, and after they had been again through the annealing furnace their resistivities were 108.7 and 107.1. The fourth time they were relaxed the specific resistances were 112.6 and 112.6, and their average diameters about 0.578 and 0.576. When they were finally hardened again, the resistivities were 136.7 and 137.8 and both diameters were 0.581. It did not seem worth while to carry the process farther.

TABLE II.

Cast Iron Rod four Times hardened and annealed.

H.	*B.*	*H.*	*B.*
1.13	57	7.70	964
1.40	79	9.15	1521
2.03	120	13.2	2910
3.31	222	20.6	4585
4.40	326	32.7	6030
5.75	518	42.4	6430
6.54	681		

Another rod, presumably of a very different kind of iron, began with a diameter of 0.574 and after four annealings had a mean diameter of 0.578. Its resistivity in the relaxed state rose in four steps from 93.9 to 102.5; the first time it was hardened its resistivity was 112.0, the last time 116.5.

In the three cases here mentioned the specimens would cut common window glass easily the first time they were hardened; they were mechanically too soft to scratch the same glass when, having been repeatedly hardened and relaxed, they were finally hardened so that they had a higher resistivity than at first.

Another rod from the same foundry had a resistivity of 102.0 when it was first annealed, and a resistivity of 119.8 when it was hardened for the first time. After an hour in steam at 100° this fell to 118.0, and after five hours farther steaming to 116.6. The second time it was annealed the rod had a resistivity of 106.5, and the third time of 107.2.

The temperature coefficient of the resistivity of the first rod spoken of above was 0.00102 when the rod was soft; the third rod had a temperature coefficient of 0.00094.

Cast iron which has been several times hardened and annealed is finally in its annealed state not so permeable as once-annealed soft cast iron is. Table II gives the results of tests upon a rod of resistivity 98.3 which has been four times heated white hot and chilled and then annealed.

If the process of heating and chilling a number of cast-iron rods be carried out many times in succession without proper annealing after each chilling, there does not seem to be a progressive increase in the resistivity; the results are anomalous.

Several kinds of chilling baths were used for hardening the cast iron, among them ice cold water, cold brine, sulphuric acid and water, an acid bath (X) the constitution of which is a trade secret, but which, I understand, has been much used in commercial work; mineral oil, and paraffine.

It has long been known that in the hardening of tool steel from a dull red heat, it is much more important that the fall of the temperature of the piece down to say 300° C. shall be quickly brought about than that the rest of the journey to room temperatures shall be rapid. It is not difficult to cool quickly a slender rod, but a large piece of hot metal suddenly immersed in a water bath is immediately surrounded by a layer of steam and, unless the water be very vigorously stirred as in die hardening, the metal may remain red hot for a comparatively long time. Many attempts have been made by varying the chemical nature of the bath to lessen the effect of the steam cloak, and some persons have used a bath of easily fusible metal for the first part of the chilling process (as is now the practice for some of the new high power steels), and have completed the cooling in a water bath, the temperature of which within wide limits seems to be unimportant.

In the light of the behavior of steel, it seemed unlikely that in the hardening of cast iron from a temperature much higher than can be used with ordinary tool steel, there would be much advantage in making the hardening baths especially cold, and experience justified this assumption. Sometimes the hardening bath was chilled with ice, but usually it was used at room temperatures or even lukewarm.

For rods of the dimensions of the test pieces I used, water, brine, sulphuric acid and water, and the X mixture seemed almost equally effective in making the cast iron glass-hard, whether resistivity or magnetic permeability of the hardened piece was used as the criterion.

For massive pieces of iron the X mixture, which certainly is very good, is said to work more uniformly than a water bath. Several specimens which were chilled in iced water and iced brine developed minute cracks which showed in irregularities when the rods were magnetized, but these, which were tested before the construction of the special gas furnace, may not have been uniformly heated. The oil bath was nearly as good, so far as increasing the resistivity of the specimen, as the water bath, but the hardened pieces did not seem so hard mechanically. The melted paraffine wax, at as low a temperature as would keep the wax liquid, also increased the resistivity of a specimen chilled in it, provided it had not been hardened before, quite as much as the water bath, but a piece thus hardened would not scratch glass.

Most of the pieces of American cast iron which I have tested had, when soft, resistivities referred to the centimeter cube, which at 0° C.

TABLE III.

Grid.	s.	a.
I	76.5	0.00104
II	86.1	0.00106
III	89.9	0.00099
IV	94.2	0.00084

would lie between 73 microhms and 104 microhms. These pieces when hardened for the first time had resistivities which at the same temperature lay between 80 and 126. Nine pieces of American cast iron tested when soft by Barus and Strouhal had on the average a resistivity at 20° C. of about 79.1 microhms with a temperature coefficient of 0.00120. Four grids, typical of the softer kinds of iron which I have used, gave on the average when soft at the same temperature the results which appear in Table III.

To show the effect of hardening upon the temperature coefficient of the resistivity, I may instance six specimens with three different coefficients when hard. (See Table IV.)

When a number of steel bars of the same length and cut from the same long rod are hardened and are then magnetized in the same solenoid and aged, it frequently happens, as is well known, that the ultimate magnetic moments of the bars differ somewhat widely from one another; and the same thing is true of magnets made from cast-iron rods cut from the same grid. In Table V are given the magnetic

TABLE IV.

Rod.	s'.	a'.	s''.	a''.
1	94	0.00086	114	0.00070
2	97	0.00085	117	0.00070
3	79	0.00105	103	0.00086
4	75	0.00108	102	0.00086
5	88	0.00103	113	0.00091
6	86	0.00106	117	0.00091

s' and s'' are the resistivities at 20° C. in the soft and in the glass-hard states, respectively; a' and a'' are the temperature coefficients.

moments (M) and the temperature coefficients of the moments (k) of eight typical bar magnets which have been tested with great care by Mr. John Coulson.

TABLE V.

Grid.	Rod.	M.	k.	Chilling bath.	s.
A	1	1550	0.00022	Water	110
A	2	1580	22	Water	104
B	3	1720	24	Water	94
B	4	1740	26	Water	94
B	5	1560	26	H_2SO_4 and water	96
C	6	1410	27	H_2SO_4 and water	109
C	7	1500	27	H_2SO_4 and water	106
C	8	1600	27	"X" mixture	106

Mr. Coulson tested at the same time three magnets of the same dimensions as these but made of glass-hard Stubs tool steel. They had on the average a moment of about 1690 and a temperature coefficient of about 0.00095, which is more than three times as large as the corresponding value for cast iron.

After the moments of the eight cast-iron magnets had been determined, the rods were thoroughly demagnetized inside a solenoid through which a long series of currents, gradually decreasing in intensity and alternating in direction, could be sent. Then each was placed inside another solenoid and an HB diagram was found for it by the method

of ascending reversals with the aid of a small test coil about its centre and a ballistic galvanometer of period sufficiently long for the purpose. Each rod was about 50.9 of its own diameters long and, according to

TABLE VI.

H.	*B*.	*H*.	*B*.
10	310	70	4250
20	720	80	4950
30	1290	90	5550
40	2100	100	5950
50	2870	120	6480
60	4100		

the formula of Dr. Shuddemagen for the end corrections of rods of these dimensions, the actual magnetic intensity (H) inside the metal at the centre is equal to $H' - 0.00107\ B$, where H' is the force inside the solenoid when the rod is removed. It is possible, therefore, to

TABLE VII.

Rod.	H_{1000}.	B_{120}.
A 1	26.3	6020
A 2	25.9	6200
B 3	26.5	6480
B 4	25.9	6480
B 5	25.2	6180
C 6	25.9	5960
C 7	26.1	6045
C 8	25.8	6150

determine very approximately the relative values of H and B from the observed values of H' and B, and the computation has been made by Mr. Coulson for these rods. The results of this work show that though the moments of the magnets differed so much among themselves, the permeabilities of the pieces of metal for excitations up to $H = 50$, at least, are much the same. Magnet B4, for instance, had a moment

much larger than the moment of C6, but the value of H corresponding to an induction of 1000 was in each case about 25.9.

For the rod B4 the relation between H and B is indicated approximately at all events by the numbers given in Table VI.

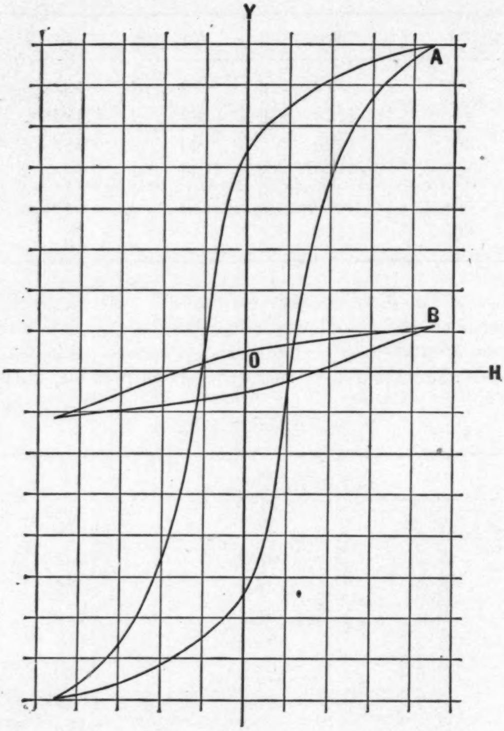

FIGURE 1.

Table VII gives under H_{1000} the value of the excitation corresponding to $B = 1000$, and under B_{120} the value of the induction corresponding to $H = 120$ for all the rods.

The specimens used were cast at different times in order that they might fairly represent the best mixtures used by the foundries from which they came, and in view of this fact the near agreement of the

measurements recorded in this table is very striking. The differences are not greater than one might expect to find in a number of rods of fine polished drill rod from the same lot. For the present discussion it is of interest to notice that the permeabilities of the hard rods seem not to be connected in any obvious way with the resistivities. For any single specimen of cast iron, however, it is well known that hardening usually decreases the permeability especially at comparatively low excitations, and Figure 1 shows a rough kind of hysteresis diagram which I obtained some years ago for a cast-iron frame of several kilograms weight. Curve A corresponds to the soft state and B to the

TABLE VIII.

H.	*B.* (Rod hard.)	*B.* (Rod soft.)
100	6800	9650
200	8850	11160
300	10310	12460
400	11420	13550
500	12130	14400
600	12660	14980
10000	25650	28250
11000	26600	29300
12000	27500	30400
13000	28450	31300
14000	29400	32050
15000	30350	33600

hardened state of the same piece of iron. At high excitations the difference is not so striking but is very real.

Table VIII gives approximately the results of some measurements made two or three years ago upon cylinders and isthmuses of a certain kind of cast iron from the Broadway Iron Foundry. It must be clearly understood, however, that this applies only to iron which has once been through the annealing and subsequent hardening. A repetition of the process makes the hardened iron mechanically softer. As we have seen, a piece of cast iron properly hardened for the first time makes as strong a permanent magnet as a piece of Stubs Drill Rod does, but if the cast iron be several times hardened it be-

comes incapable of retaining the charge given it in the solenoid and the resulting magnet is perhaps only half as strong as the steel magnet.

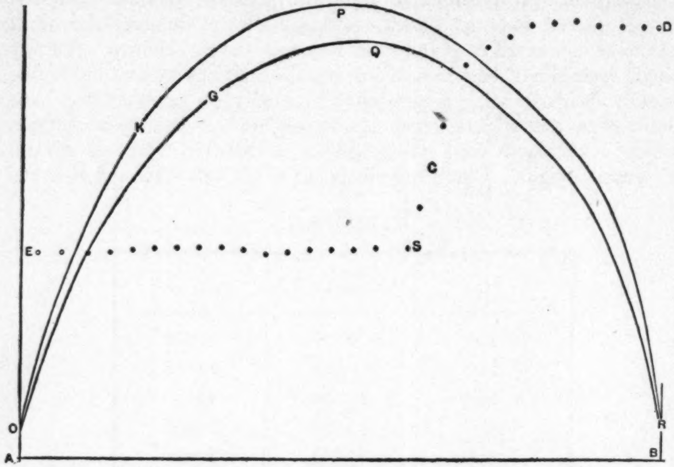

FIGURE 2.

The same phenomenon appears in the case of tool steel, though it is not very easy to harden a piece of tool steel glass-hard a number of times in succession without working it under the hammer to avoid the appearance of minute cracks in the metal.

FIGURE 3.

For many years small magnets made of cast iron as it comes from the founder have been used in toys and in small "magnetos," but such magnets are not nearly permanent and are not so strong at the outset as similar magnets made of properly chilled iron. A certain annealed rod which I tested had when magnetized to saturation a moment of 605 on a certain scale, but a few minutes in boiling water reduced this to 455; when the rod had been hardened and again magnetized, its moment on the same scale as

before was 831 and boiling reduced this to 740. The same magnetized castings are tested year after year in the Jefferson Laboratory, and so far as my experience goes, a properly hardened and aged magnet made of cast iron is quite permanent if it is exposed to such fields as that

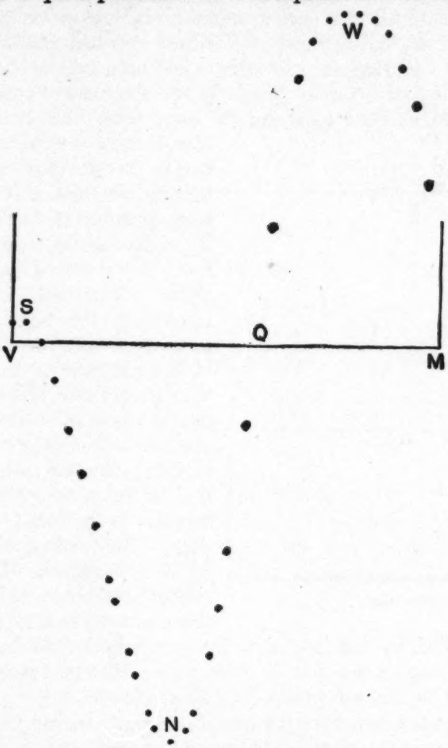

FIGURE 4.

of the earth, and mechanical shocks do not injure them in any way, if the metal is not broken or abraded.

Although a knowledge of the resistivity of a piece of cast iron tells very little about its temper unless one knows also its resistivity in the annealed state, yet the resistivity of different portions of the same piece is a trustworthy measure of the uniformity of temper. Tried by

this test, many a piece of steel which has been hardened with care proves to be far from homogeneous.

Occasionally great differences of resistivity may be found in a magnetized steel rod which yields a fairly uniform iron-filing diagram.

The curve OKPR of Figure 2 shows the induction flux (B) at different points of the axis of a rod of Crescent Polished Drill Rod 29 cm. long and 0.5 cm. diameter just after it had been magnetized to saturation in a solenoid. Curve OGQR shows the same quantity after the rod had been exposed to steam for some time. AB is the common base of these curves. The distribution is in each case nearly uniform, and the iron-filing curve seems entirely so, but the resistivity of the metal is far from uniform, as the dotted diagram ESCD shows. This was obtained by measuring the resistances of a large number of very short lengths of the rod and determining from the results values for the resistance per centimeter at about thirty points on the axis. Of course a small portion at each end could not be treated in this way, and the fact is indicated by the open dots. One end of this bar was in the soft state in which this excellent steel comes in the market; the other end had been heated red hot and chilled, so that its resistivity was quite double that of the soft end. This magnet was not so strong as a hardened magnet of this steel should be, but was otherwise normal enough.

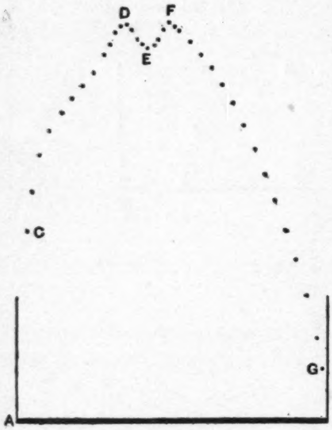

FIGURE 5.

Sometimes the iron-filing diagram belonging to a bar magnet seems very irregular when the distribution of magnetism in the metal is not very abnormal. Figure A shows a filing diagram belonging to a piece of Crescent steel of the same dimensions as that just described, while Figure 3 shows the values of B at different points in the axis. The "centre of gravity" of the magnetism is in this case not far distant from the middle of the bar. This same bar was remagnetized by rubbing a point near its centre upon one pole of a large motor, and then gave a filing diagram represented by Figure B. Here there are real consequent poles, and the distribution of the induction flux in the bar is

shown by Figure 4. After this rod had been demagnetized as well as possible in a solenoid by the use of a series of currents alternating in direction and gradually decreasing in intensity, and then had been magnetized again to saturation in a solenoid as before, Diagram A came back again.

Another unequally hardened steel rod of the same kind gave the filing diagram shown in Figure C, and in this case the distribution of magnetism was that indicated in Figure 5.

Figure 6 shows in the curve HYU, of which the horizontal line through E is the base, the resistivity of a rod of cast iron of the dimensions of the specimens used in this investigation. For this particular piece the resistivity at one end corresponded to the annealed state and at the other end to glass-hardness. After this rod had been magnetized in a solenoid, the distribution of magnetism in it was that represented by the dotted curve GZX. This rod when magnetized irregularly on the motor gave the diagram LCK, but when the rod was demagnetized and again magnetized in the solenoid, the distribution GZX returned. It is interesting to notice that in the cases shown in Figures 4 and 6, the motor gave a smooth distribution of B while the solenoid gave an irregular one. When real consequent poles are pres-

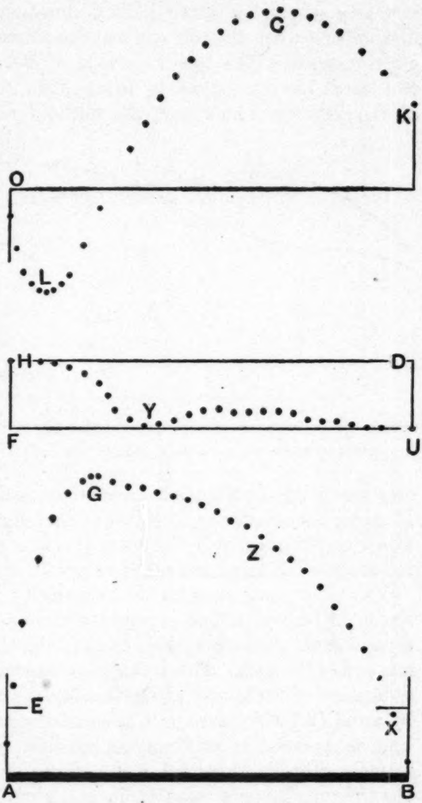

FIGURE 6.

ent, the value of B is at its greatest smaller than in the case of the solenoid magnetization.

Figure 7 shows in the curve PADQ the distribution of magnetism in an unequally hardened cast-iron rod when the magnetization took place in a long solenoid. Curve PDBQ shows on an exaggerated scale the distribution when the rod was magnetized between the poles of a large electromagnet. The greatest value of B was in this latter case about two thirds the corresponding value when the solenoid was used. In all the instances I have met, the solenoid gave the greatest value of B

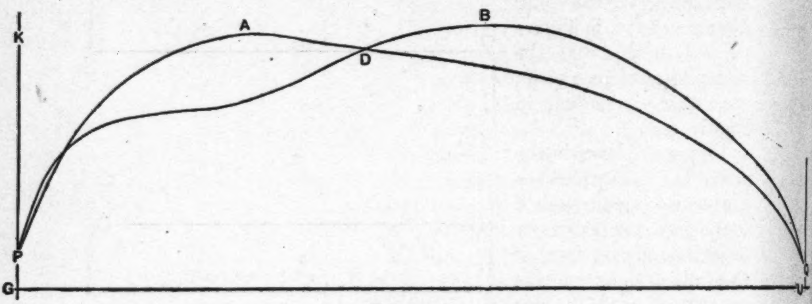

FIGURE 7.

and any other distribution gave an appreciably smaller value. Table IX gives the resistivity at points distant n cm. from the end of the rod which corresponds to G in Figure 7. It is evident that one end of the rod is glass-hard and the other very soft.

The most common form of irregularity in a cast-iron bar magnet seems to consist, if one may judge from a filing diagram, in a simple displacement of the magnetic centre from the geometric centre towards one end of the axis. This usually corresponds to a comparatively slight difference of resistivity along the bar. This case may be illustrated by a rod (K) which had once been hardened irregularly and then had been rehardened as uniformly as possible. In all such cases it is extremely difficult to get rid of the effects of careless hardening, though the irregularity may come up in a slightly different form. The next table (X) gives the resistivity of the metal, and, on an arbitrary scale, the value of B at a point distant n cm. from one end of this bar, which was 29 cm. long.

Table XI gives the resistivities and the relative values of B on the axis of a cast-iron magnet (Q) made of a rod hard in the middle and soft at the ends.

TABLE IX.

n.	*s.*	*n.*	*s.*
3	0.000121	16	0.000097
4	122	17	94
5	121	18	94
6	121	19	92
7	120	20	92
8	117	21	92
9	115	22	93
10	111	23	94
11	104	24	94
12	097	25	94
13	097	26	93
14	097	27	93
15	097		

TABLE X.

n.	*s.*	*B.*	*n.*	*s.*	*B.*
0		60	15	127	551
1		227	16	126	560
2		317	17	126	568
3	121	368	18	127	572
4	118	405	19	129	578
5	119	430	20	129	580
6	118	448	21	129	578
7	120	460	22	129	573
8	121	470	23	129	565
9	121	480	24	126	535
10	122	493	25	125	505
11	123	509	26	124	453
12	123	520	27		374
13	126	532	28		260
14	126	541	29		72

TABLE XI.

n.	*s.*	*B.*	*n.*	*s.*	*B.*
0		40	15	155	412
1		140	16	150	429
2		207	17	147	445
3	117	261	18	141	458
4	119	305	19	128	448
5	117	339	20	119	433
6	118	371	21	118	417
7	120	394	22	117	399
8	121	416	23	116	359
9	132	434	24	115	330
10	149	440	25	113	292
11	153	428	26		257
12	153	417	27		198
13	156	409	28		135
14	158	407	29		37

If the material used in these experiments may be considered typical of the so-called "pure cast iron" from good foundries, it appears, then, that an annealed casting may have at room temperatures a resistivity, referred to the centimeter cube, as low as 0.000073 or as high as 0.000104; that it is always possible to make the specimen glass-hard throughout by heating it to a temperature a little below the melting point and chilling it in a suitable bath; and that the process, as Barus and Strouhal showed, is always accompanied by an increase in resistivity. This increase is sometimes only about ten per cent of the original value, though it is oftener nearly twenty-five per cent and may rise somewhat higher. Only one kind of iron that I used resisted successfully a noticeable relaxation of temper in the hardened pieces by prolonged boiling in water. Of two pieces of iron from the same pouring, which have equal resistivities when first annealed, that one has the higher resistivity, after both have been hardened, which has the lower magnetic permeability. Tests of mechanical hardness are

difficult to make upon cast iron and often disagree with the resistivity test. A repetition of the annealing and hardening process increases somewhat the size of a specimen and increases the resistivity for both the annealed and the chilled states, but in the hardened state the iron is never so hard mechanically as at the first hardening, and the bar loses in great measure its magnetic retentiveness, as do most kinds of tool steel which have been through the same experience. Many kinds of chilling liquids serve to make cast iron glass-hard, but for massive pieces cold water seems not to give such uniform results as the acid bath used by some professional hardeners. The temperature coefficient (a) of the resistivity of every one of my specimens was decreased by the hardening, though this does not seem to have been the case for the special cast iron used by Barus and Strouhal, which had a larger coefficient (120) than any I used. The coefficient a is not always smallest in that one of a number of specimens of cast iron which has the largest resistivity.

Castings from different sources often show when glass-hard a very close agreement in magnetic permeability, though their resistivities and the temperature coefficients of the resistivities may differ widely. The temperature coefficient of the magnetic moment of a cast-iron bar magnet is usually not more than one third as large as that of a similar magnet made of tool steel.

A uniformly hardened cast-iron or steel rod may have been irregularly magnetized, but if it be thoroughly demagnetized and then carefully remagnetized in a solenoid, its magnetism will become regular. Only irregular hardening seems to lead to persistently irregular magnetization in the case of a bar magnet, though the use nowadays of electromagnetic crane lifters sometimes magnetizes iron and steel rods in a manner which is difficult to deal with in the laboratory. Even an irregularly hardened slender rod may usually be demagnetized well enough for all practical purposes in a solenoid which carries currents alternating in direction and gradually decreasing in intensity, but large thick pieces are very tenacious of charges once given to them. The shield of a certain Rubens Panzer galvanometer in use in the Jefferson Laboratory was twice heated white hot and was kept hot for some time in a vain attempt to get rid of a slight magnetization. The resistivity of different portions of a casting gives trustworthy information about the uniformity of the hardening. Occasionally, as in a case cited above, an irregularly hardened piece of tool steel may be magnetized nearly normally, but usually irregular hardening leads to an irregular distribution of the magnetism which shows itself in an abnormal iron-filing diagram. An unusual filing diagram does not

however, as some instances given show, always indicate that the distribution of the magnetic induction in the bar is very irregular.

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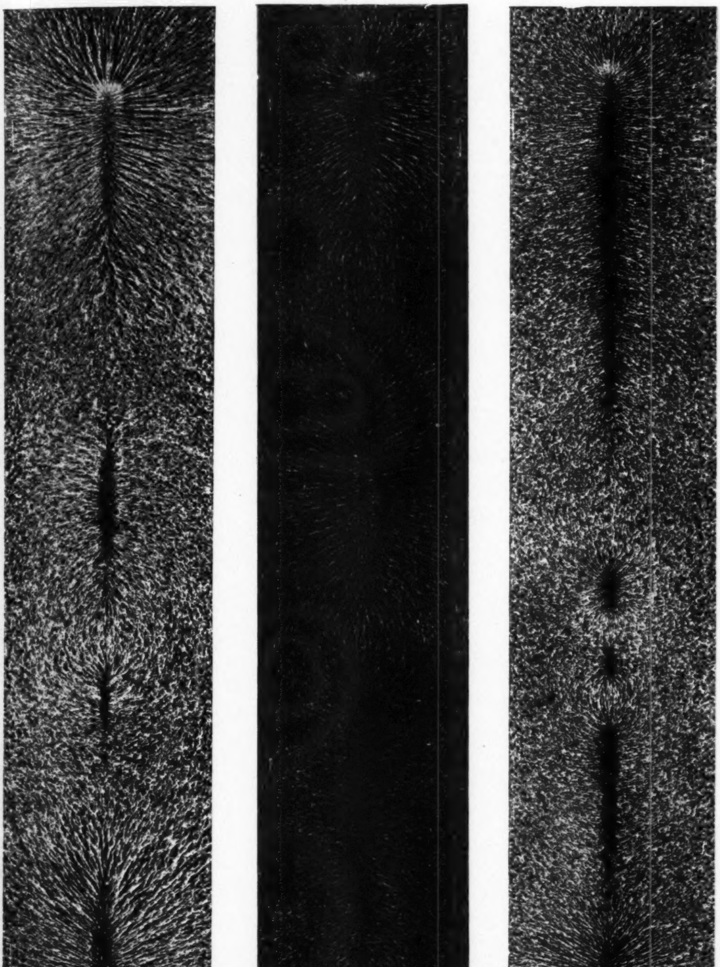

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